The Interstellar Medium: Expected Advances from Spitzer to Herschel and Beyond

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ISM Science Spitzer and Beyond

- ISM contains the history of star formation and interactions:
  - during cloud formation: radiation from [C II], [O I], and [C I]
  - star forming cores: mm-wave emission from CO and a host of other simple and complex species
  - photo-dissociation regions: radiation feedback from forming stars, emission from numerous lines in mid- to far-IR, sub-mm, mm ([C II], [O I], high-J CO)
  - shocks: mid- to far-infrared emission from H_2, water, OH, CO
- *Emission from gaseous species trace the physical conditions, are the sole tracers of dynamics, and are the primary coolants*
- Many of the key lines tracing ISM activity are not observable from the ground -- gains in our understanding of the evolution of the galactic ISM and the star formation process require space-borne platforms

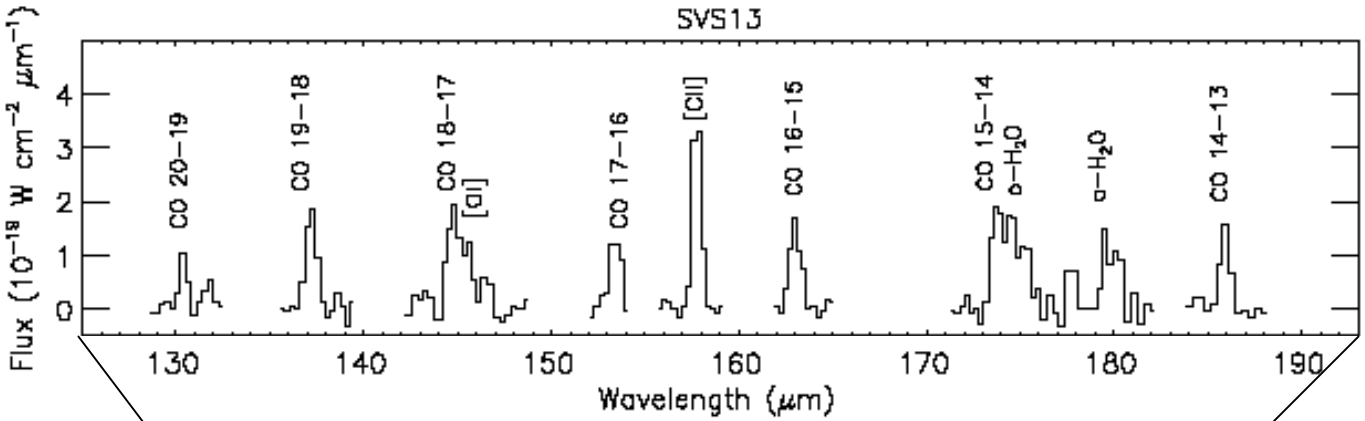
Spitzer: Anticipated Contributions to ISM Science

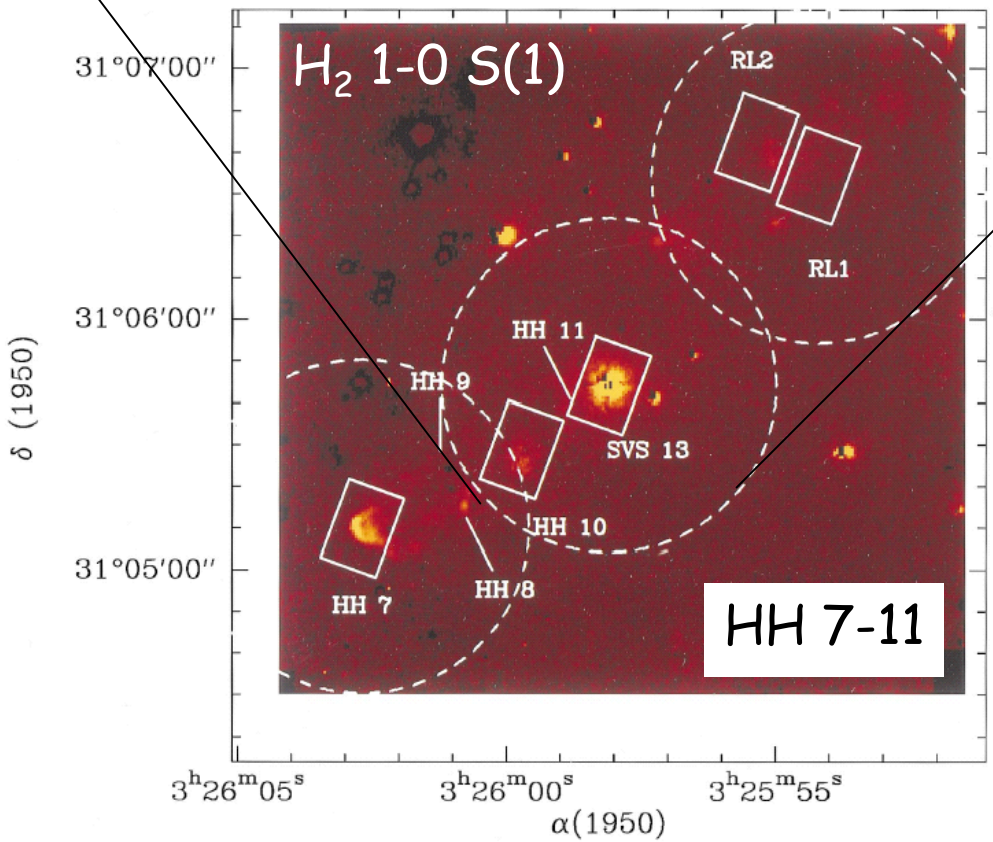
Selected Mid-IR Spectral Lines

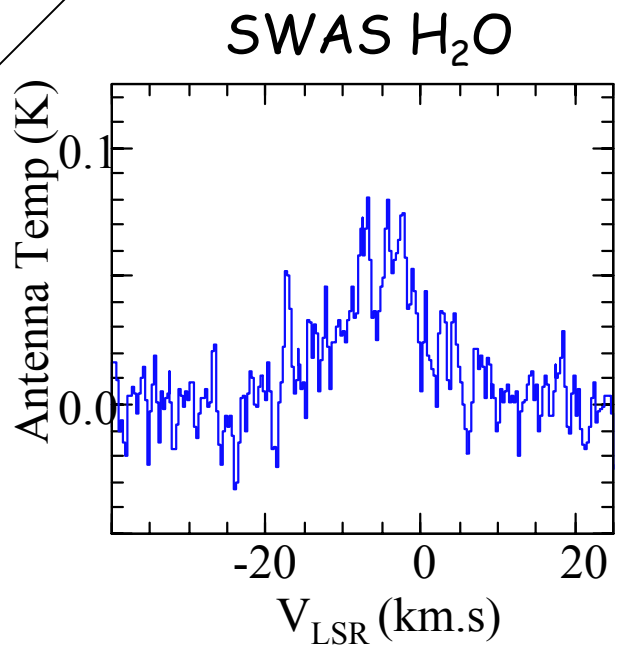
λ (μm)	Species	Diagnostic
6.0	H_2O ice	bulk of ice
6.9,8.0,9.7, 12.2,17.0,28.2	H_2 S(5-0)	PDR + shocks
7.7	CH_4 ice	organics
9.7	Silicate	bulk of dust
15.2	CO_2 ice	sur. chem.
25.2	[S I]	shocks
31.8	H_2O	shocks
34.8	[Si II]	shocks
35.5	H_2O	shocks

- major contributions to gas physics and chemistry
  - surface chemistry and ices
  - hot and warm H_2
    - shocks
    - photo-dissociation regions
  - hot H_2O
    - shocks
    - ISO and SWAS could tell water was present in shocked gas -- but were limited by angular resolution (SWAS) and sensitivity (ISO) when compared to Spitzer

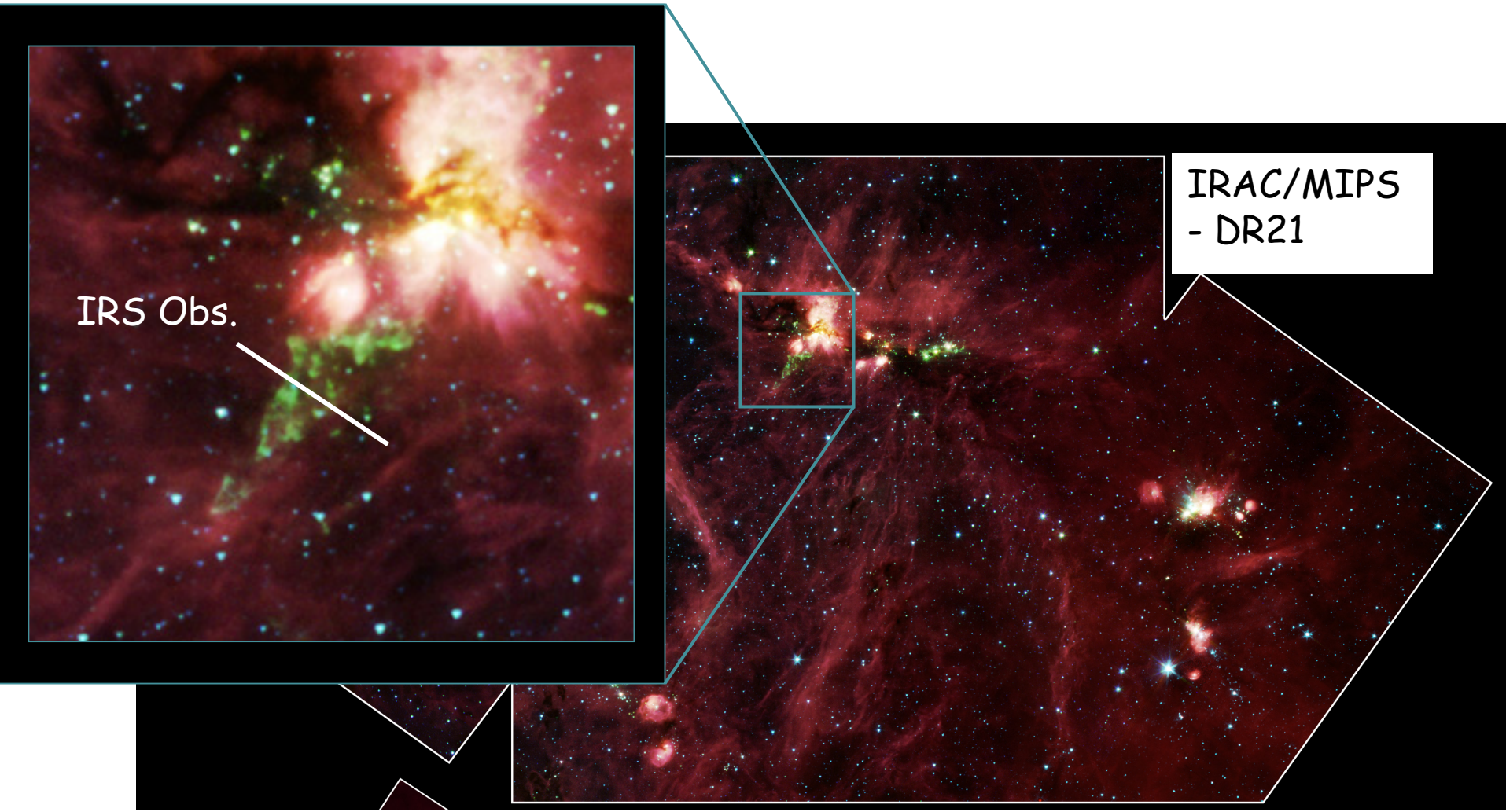
Water in Shocks: ISO and SWAS







ISM: Spitzer and Shock Physics



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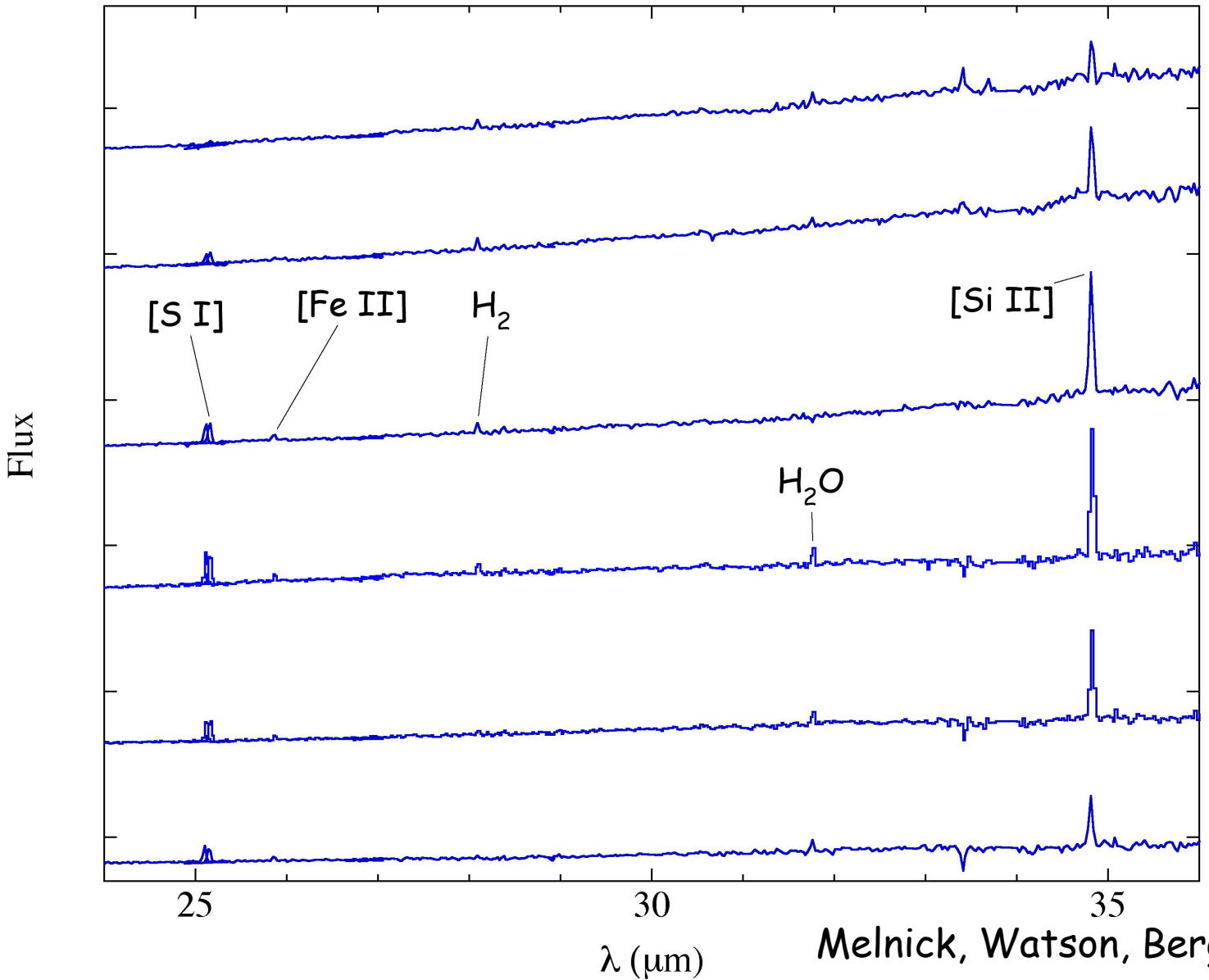
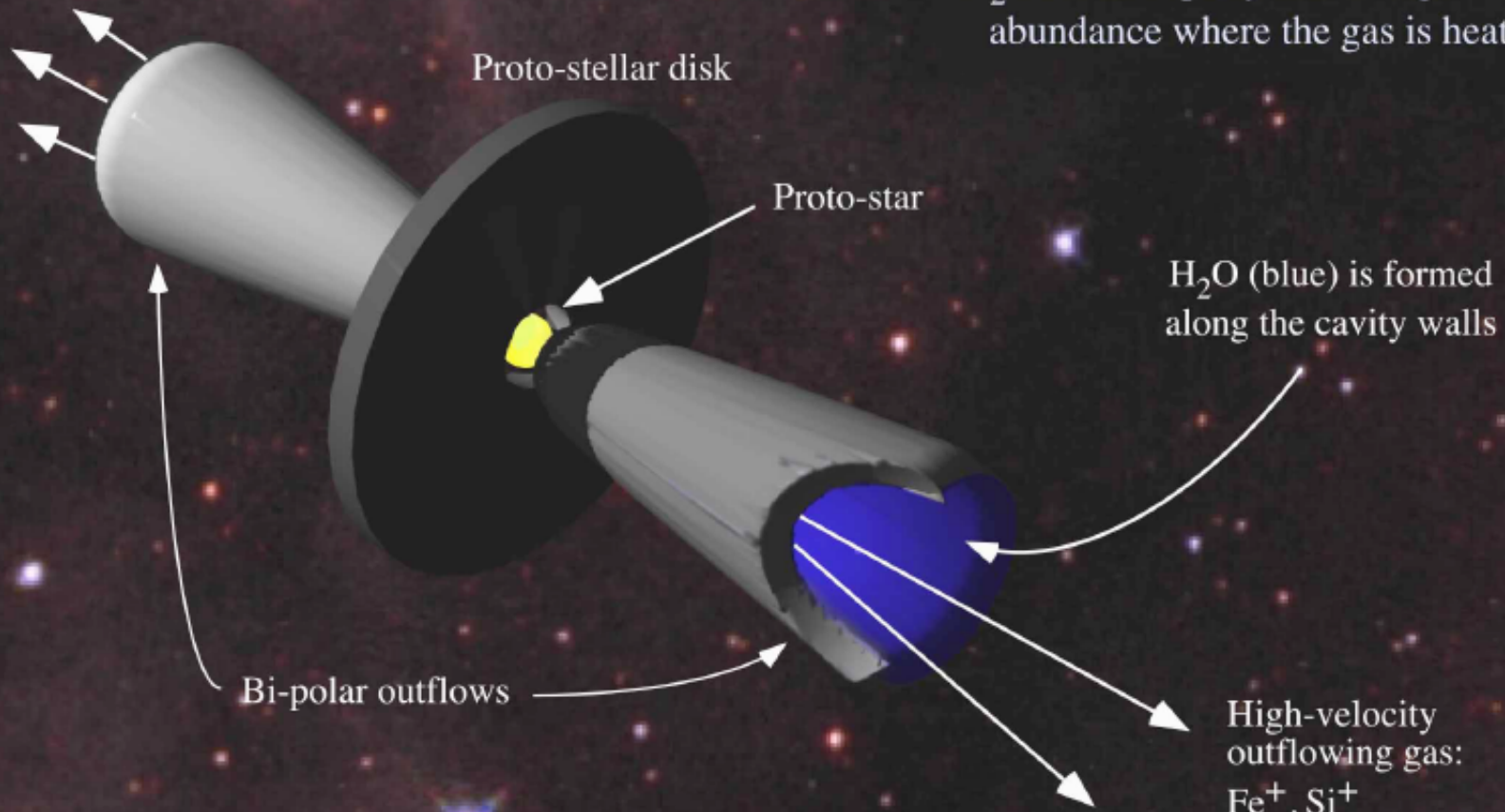


Melnick, Watson, Bergin, Smith…

Water Production Accompanies Star Formation

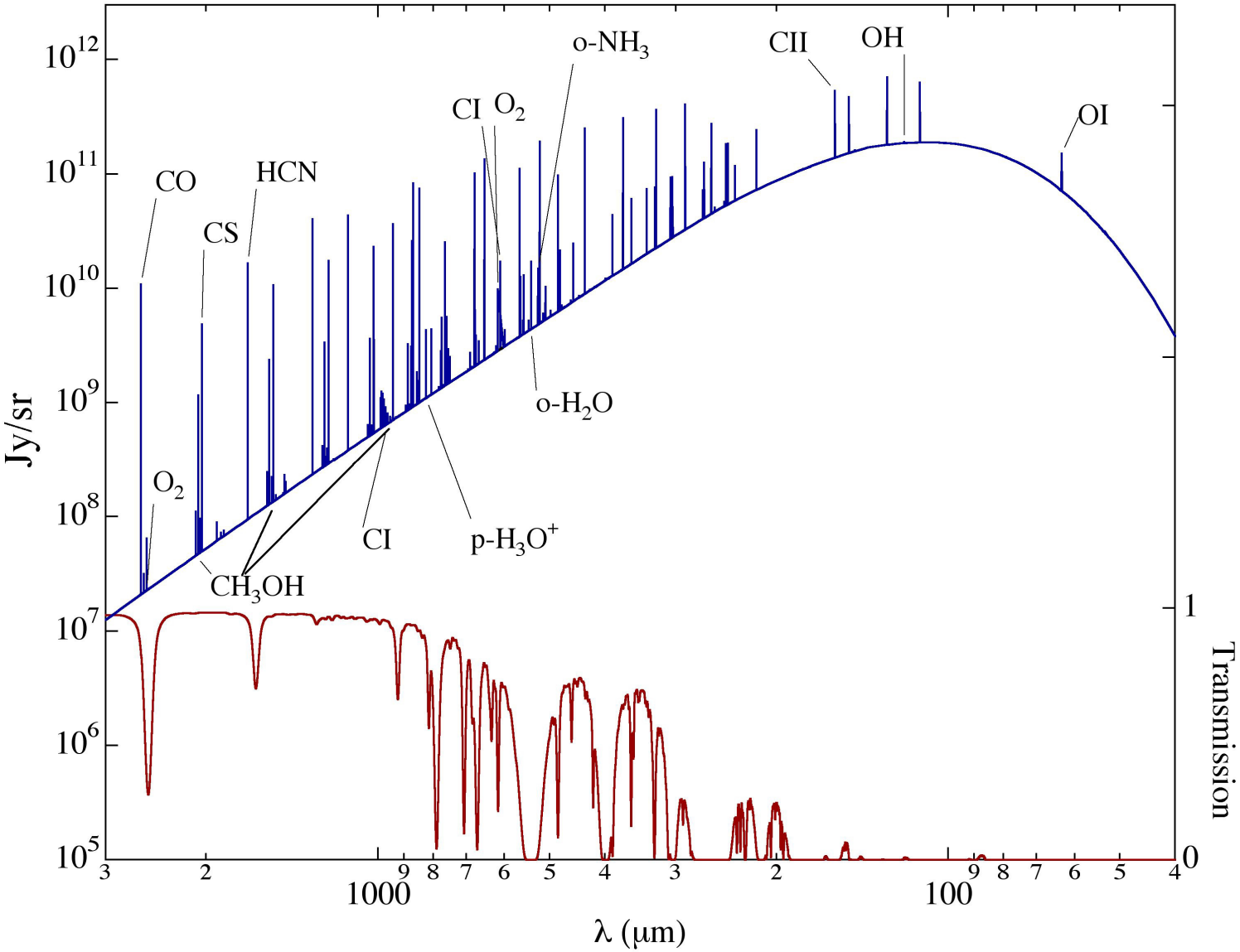
- Bipolar outflow clears a cavity on either side of the star
- High-velocity outflowing gas collides with slower-moving gas along the cavity walls, causing this gas to heat.
- H_2O forms rapidly and in high abundance where the gas is heated



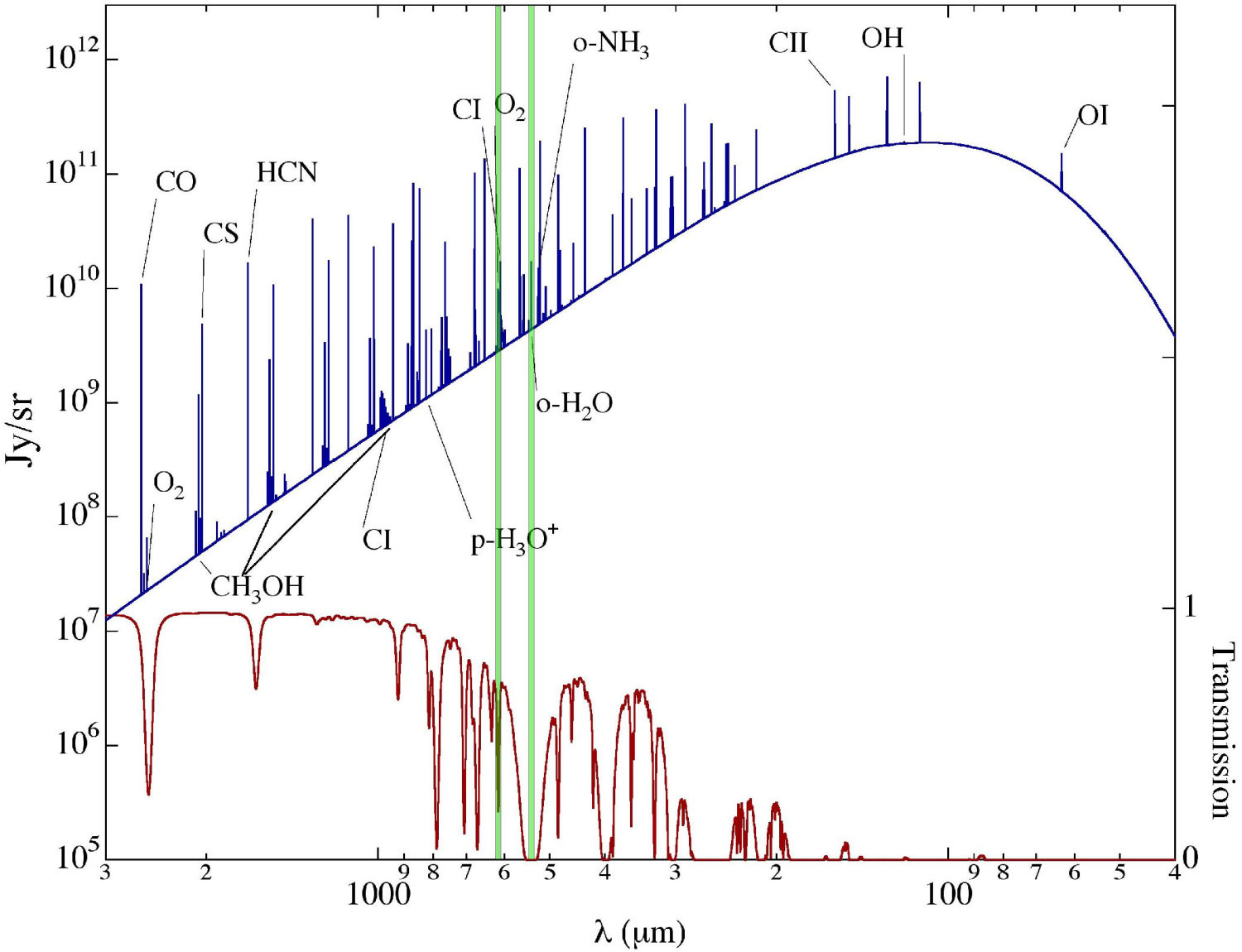
Beyond Spizter: Herschel and SOFIA

- sample ISM activity and show what will be gained from heterodyne observations from Herschel and SOFIA.
- types of activity:
  - quiescent molecular gas
  - hot core -- warm envelope surrounding massive star where ices are released leading to a complex organic chemistry
  - shocks -- example of a non-dissociative C-shock

Molecular Cloud Spectrum



Molecular Cloud Spectrum



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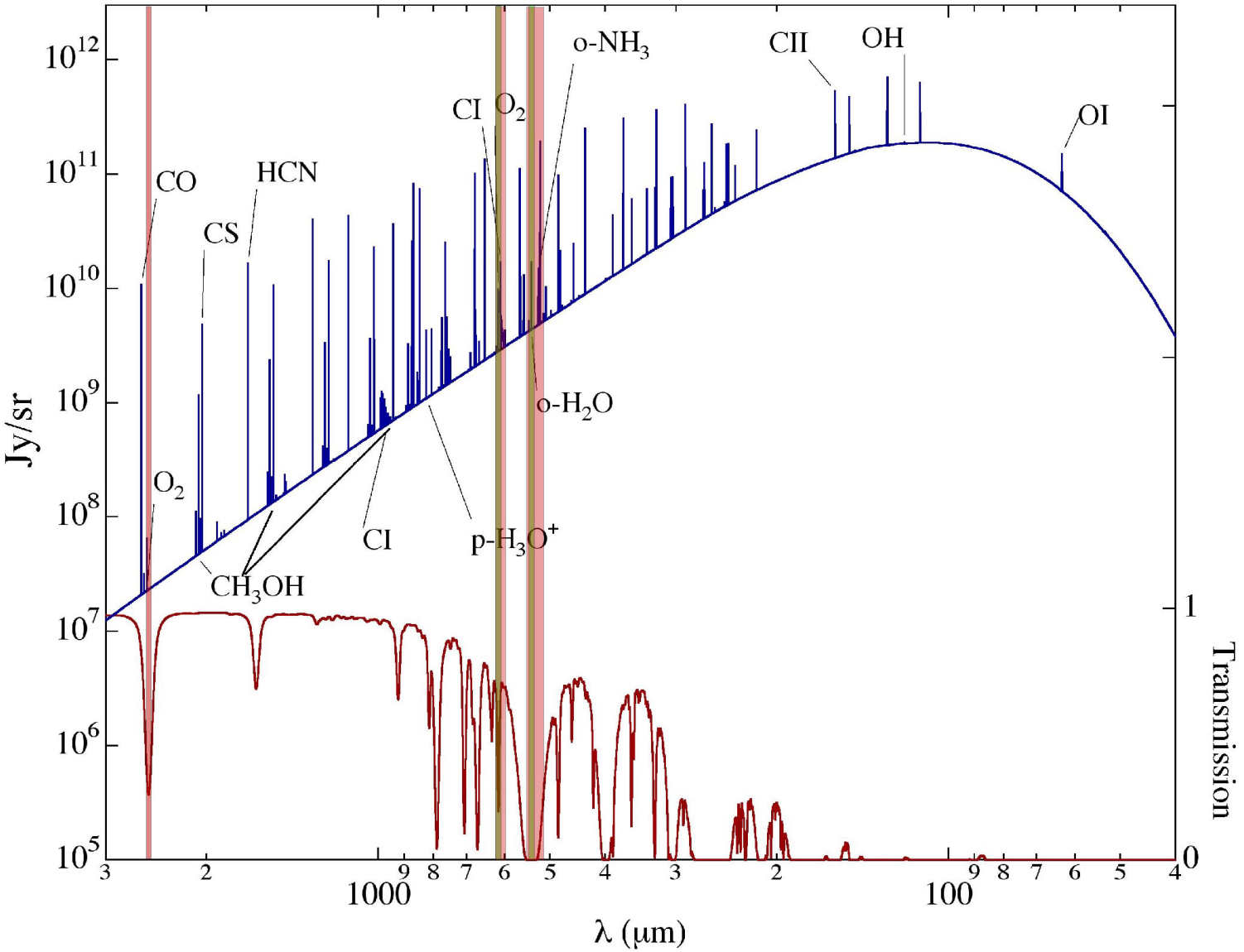

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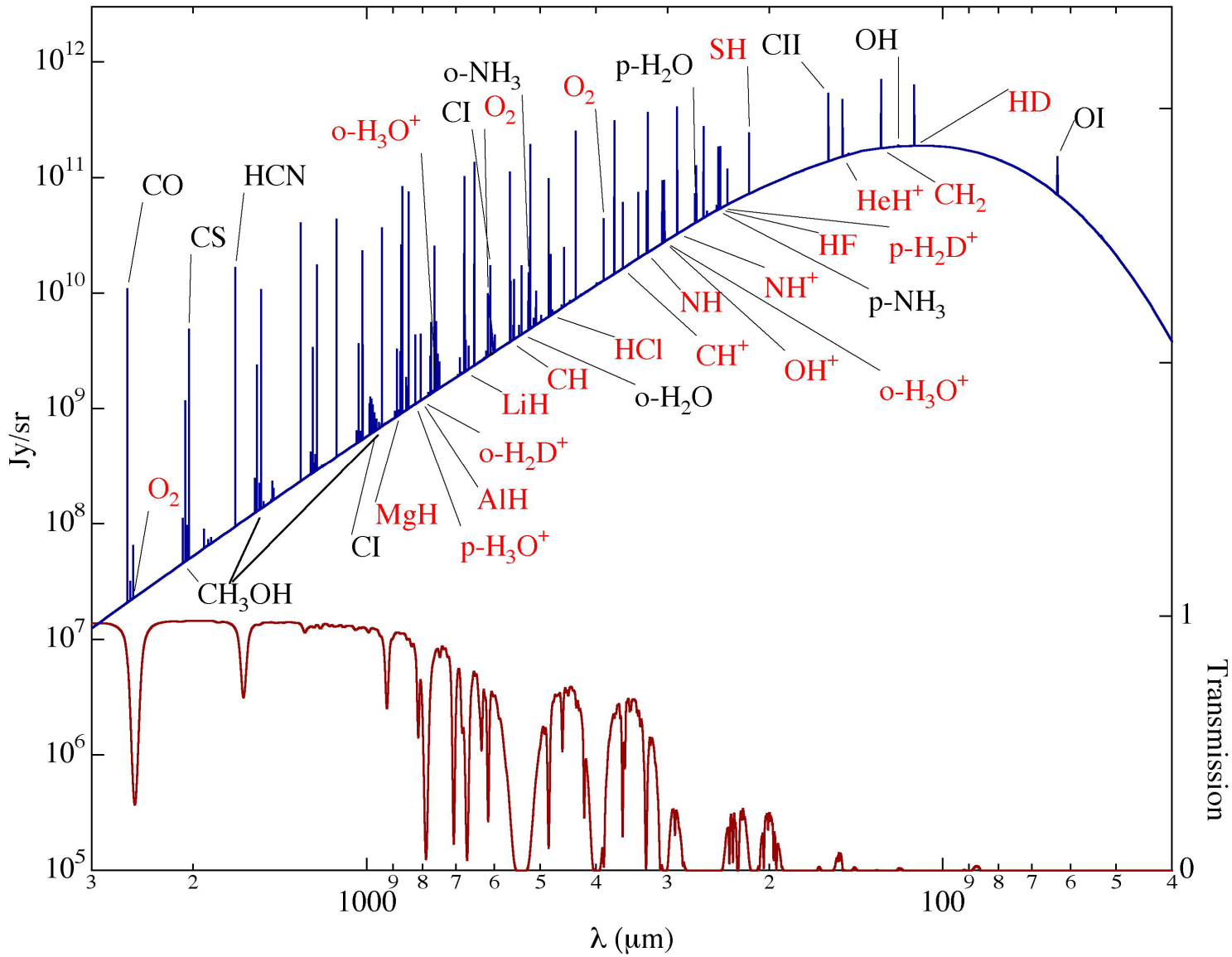

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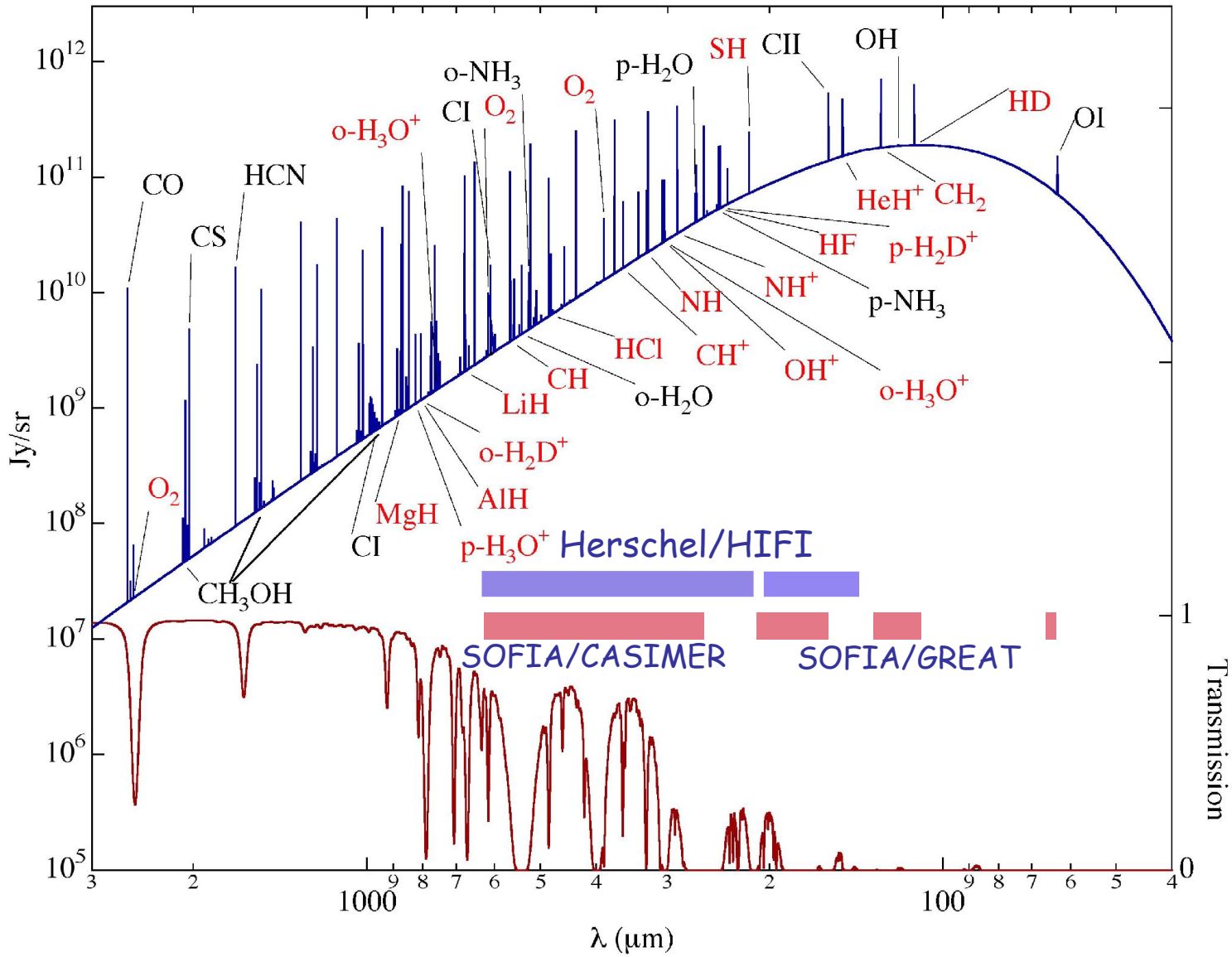
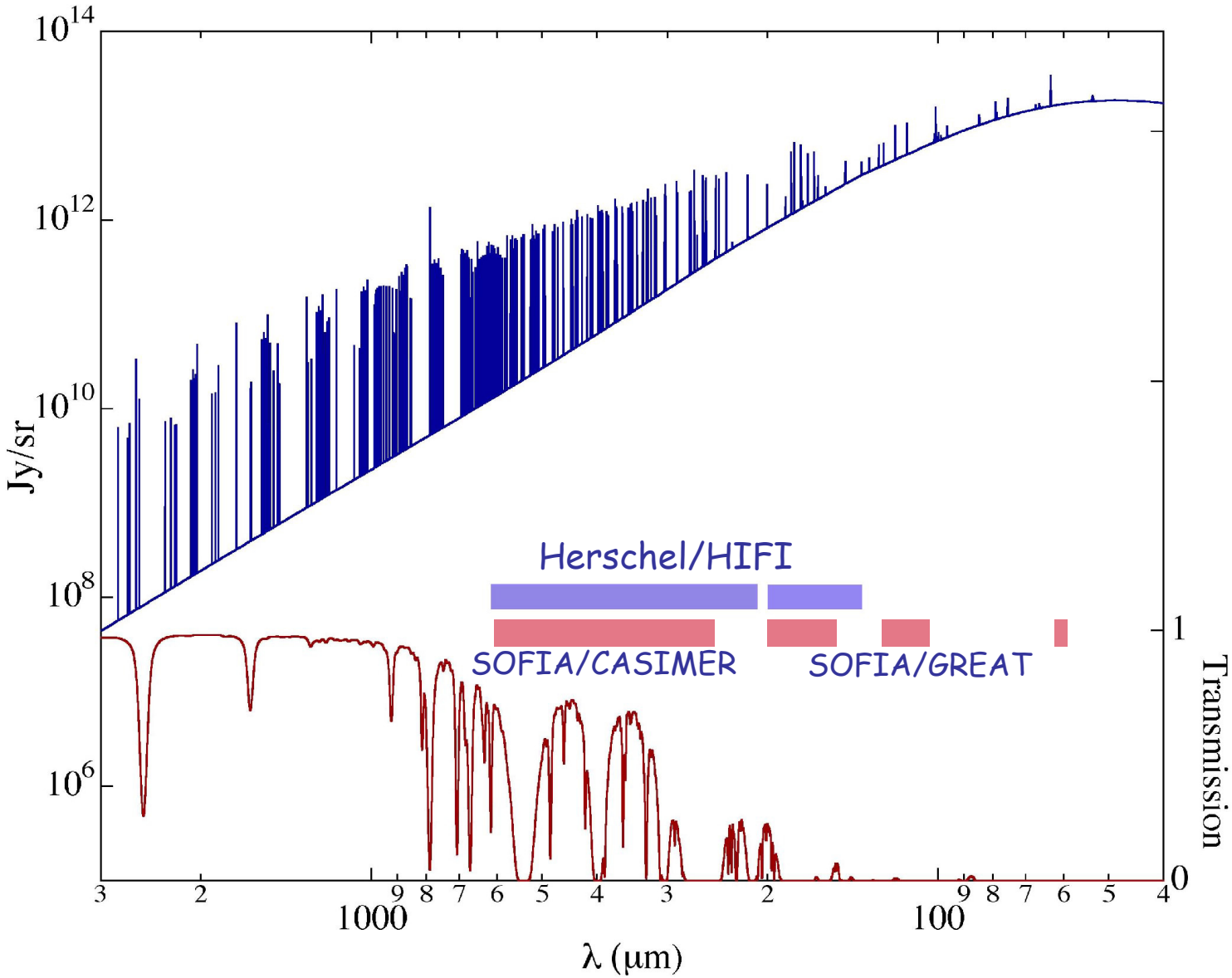
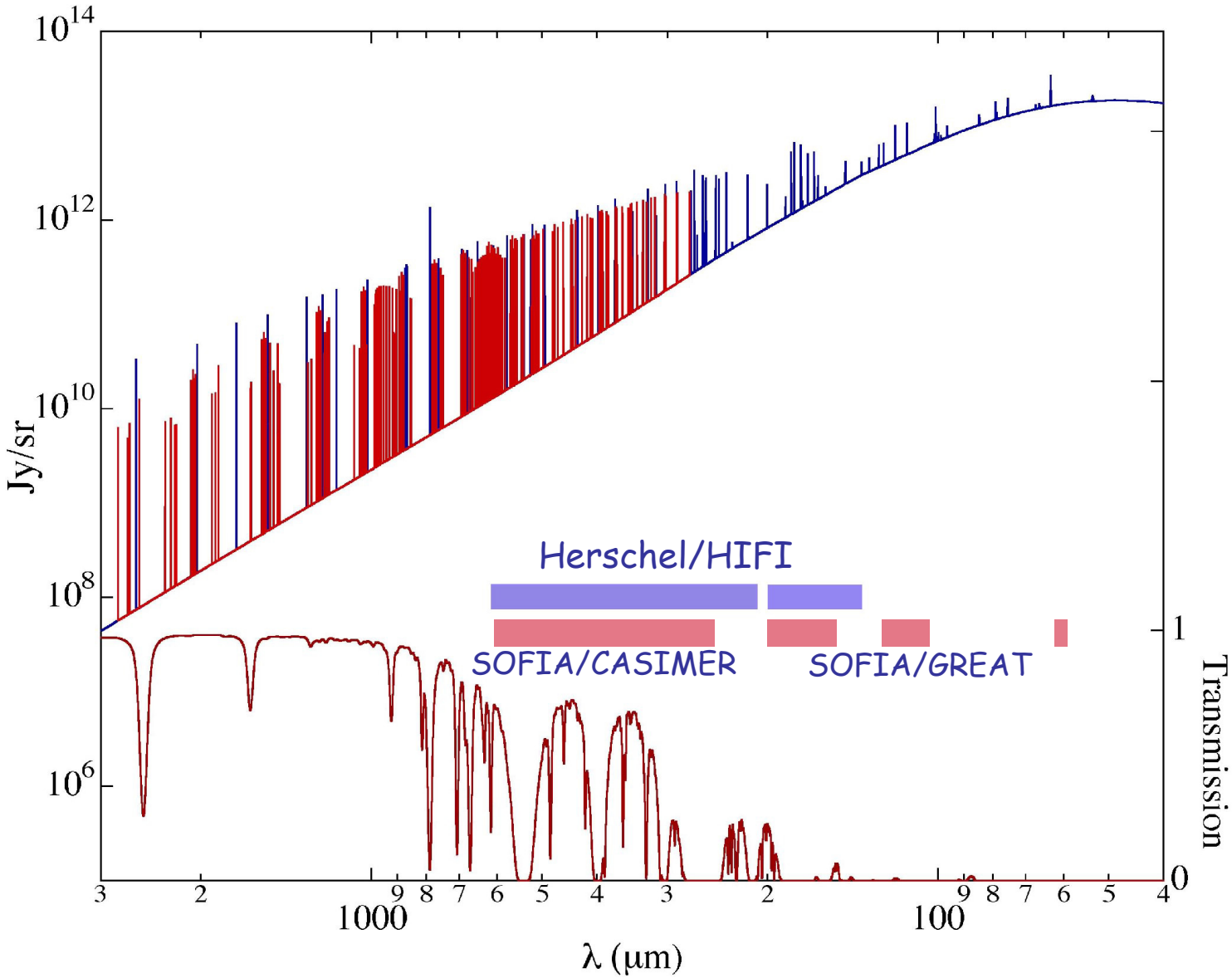


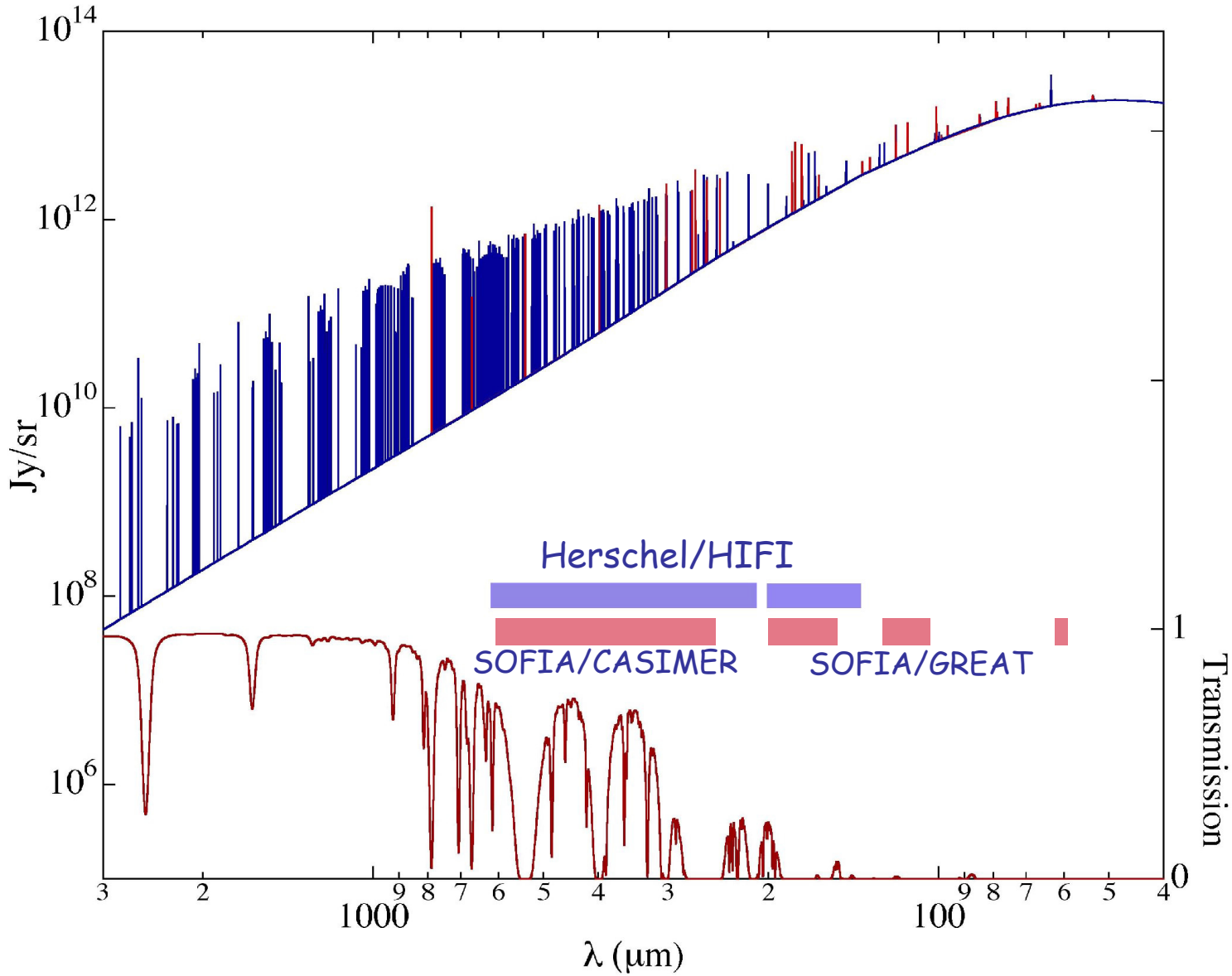
Hot Core Spectrum



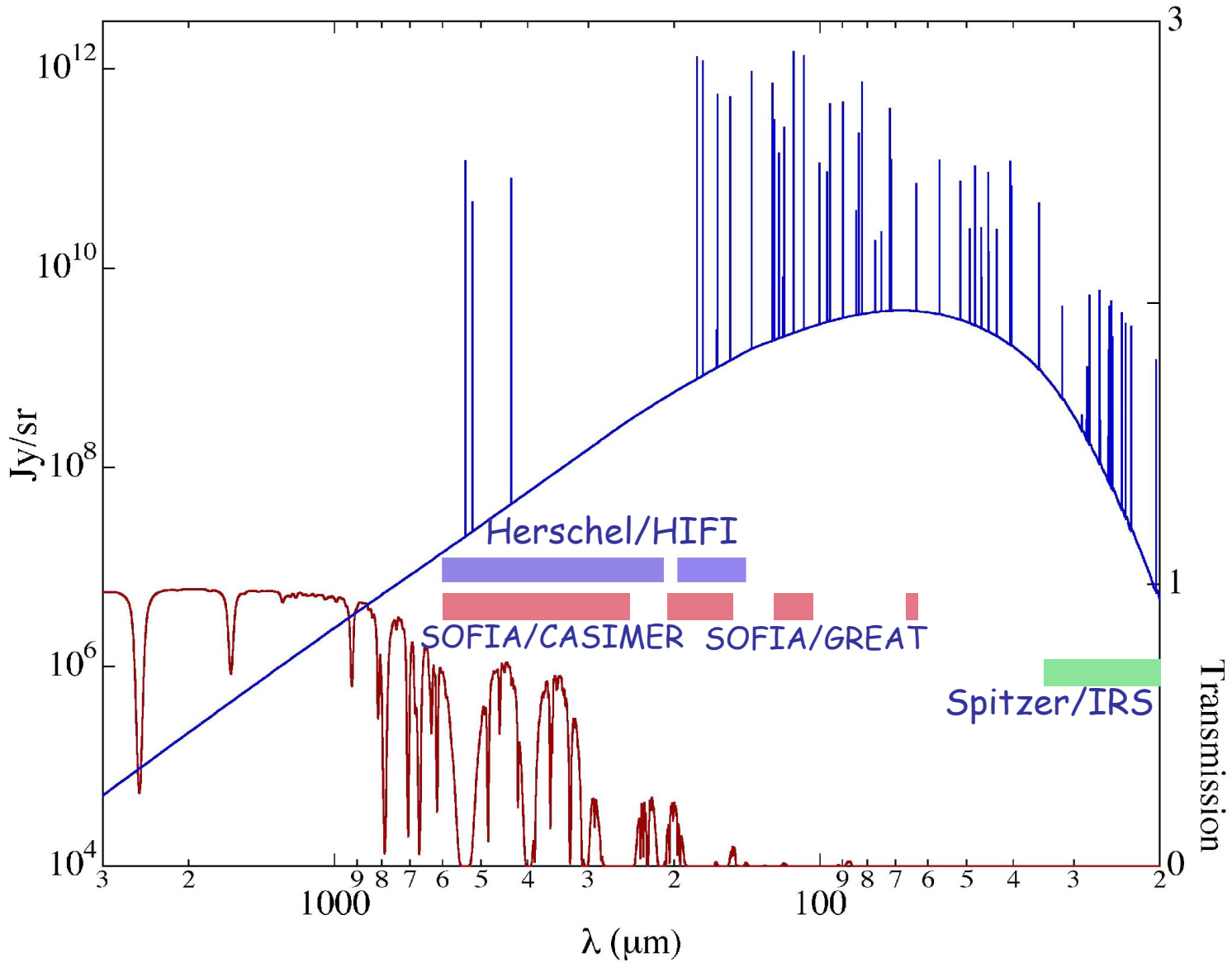
Hot Core Spectrum: CH_3OH



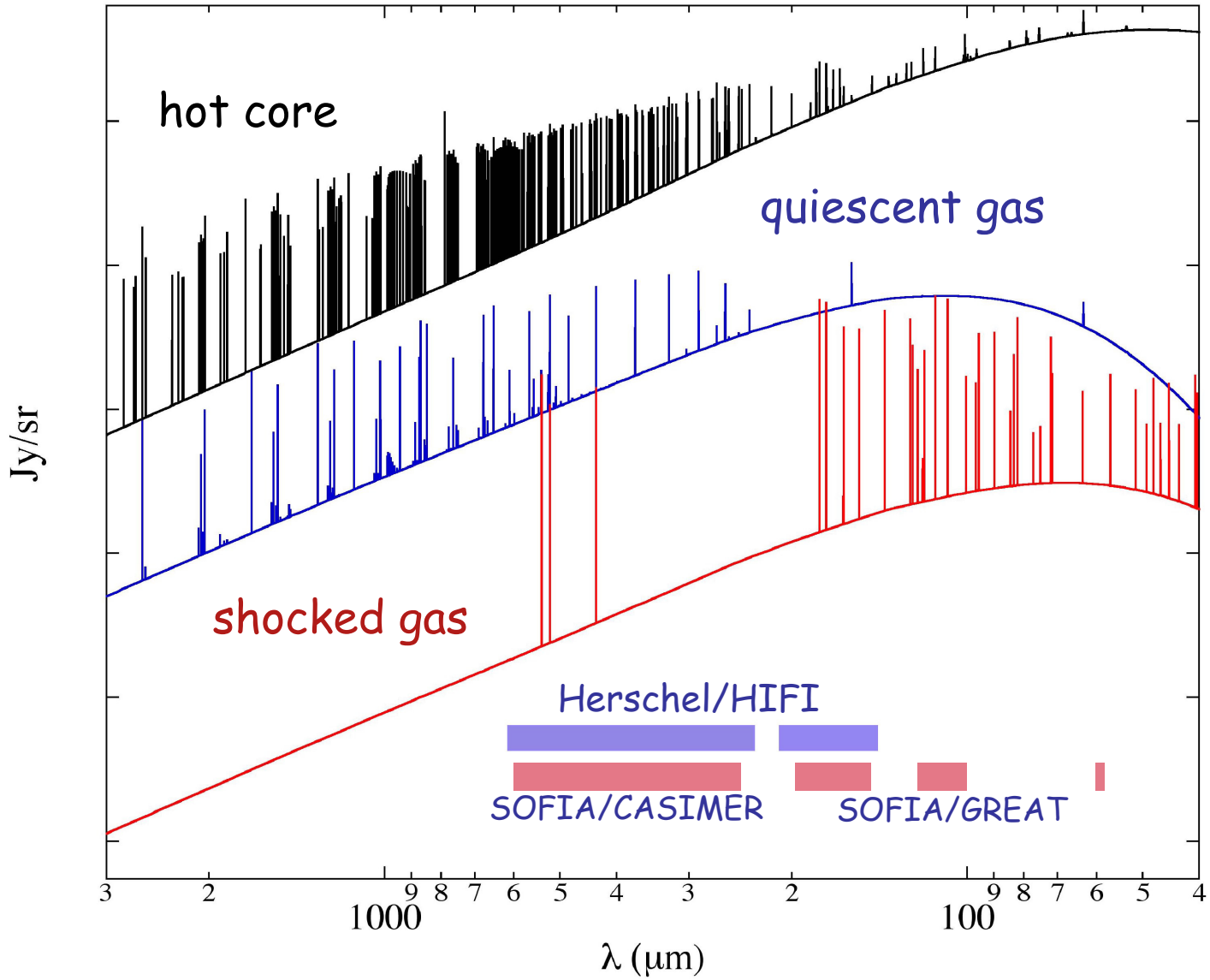
Hot Core Spectrum: Water and OH



C-Shock Spectrum: CO, H_2O, OH, H_2



The Promise of Herschel and SOFIA



Unbiased Line Surveys by HIFI

Plans for several line surveys covering a range of ISM activity (PDRs, low density clouds, hot cores, shocks)

- provide a complete chemical assay of star forming regions to some nominal limit
  - including the capability to observe species that cannot be observed from the ground (light hydrides) - some such as water are critical to understanding chemistry/thermal balance
  - track physical and chemical changes in molecular gas as a function of star formation
- provide a complete description of cloud cooling
- offer the opportunity for unanticipated results through the unbiased nature of the frequency survey

Water Cycle

- Water is one of the most important interstellar molecules --
  - gas cooling
  - oxygen chemistry
  - astrobiology (e.g. ices --> comets --> oceans)

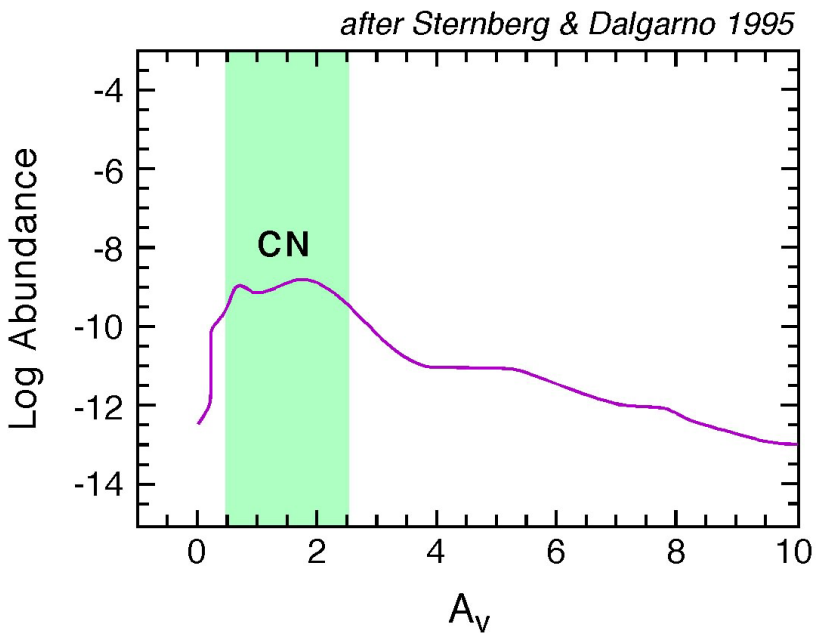
  requires space-borne platform for $H_2{}^{16}O$ observations
- What have we learned from ISO, SWAS, and ODIN?
  - in cold dense, $n(H_2) > 10^4$ cm^{-3}, ISM most oxygen not in CO is frozen on dust grains in the form of water ice.
  - in the immediate surroundings of luminous stars water is released from grain mantles (also created in shocks)
  - NEW: in quiescent gas water vapor appears to be a surface tracer

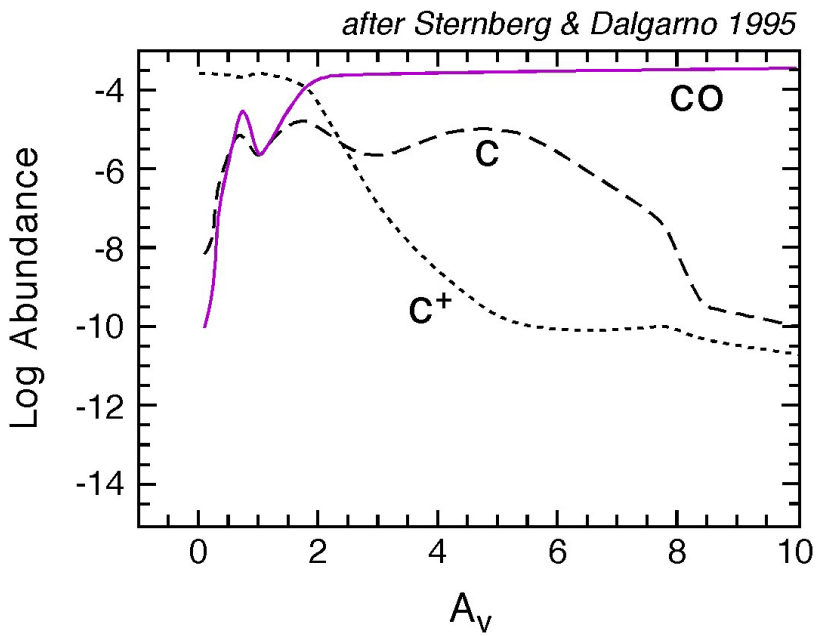
Water Cycle: Constraints from SWAS

Does the water vapor intensity correlate better with (believed) surface tracers than with (believed) volume tracers?

surface: CN

volume: $C^{18}O$



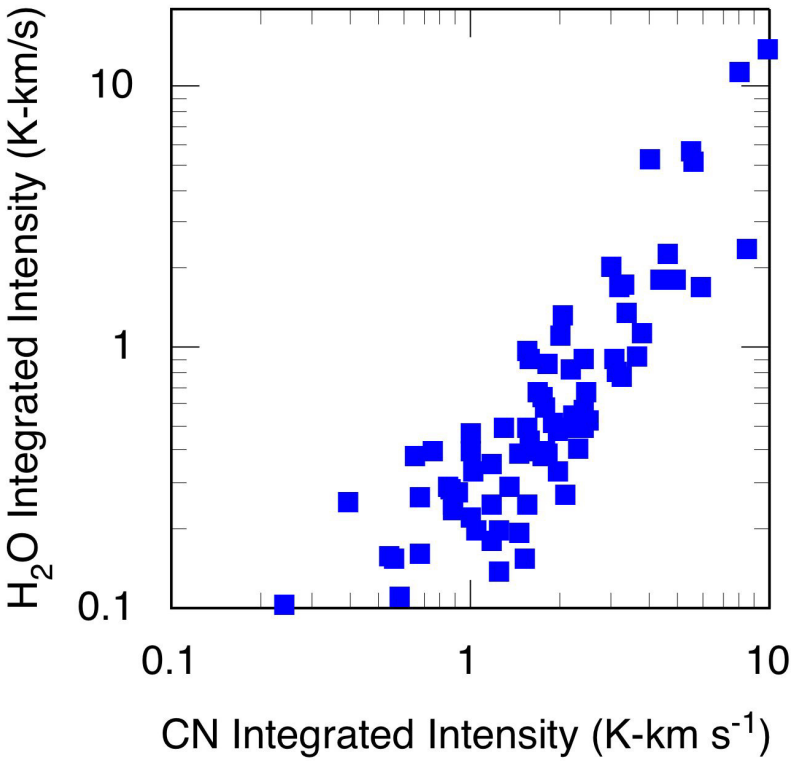


$G_o = 2 \times 10^5$; $n(H_2) = 5 \times 10^5$ cm^{-3}

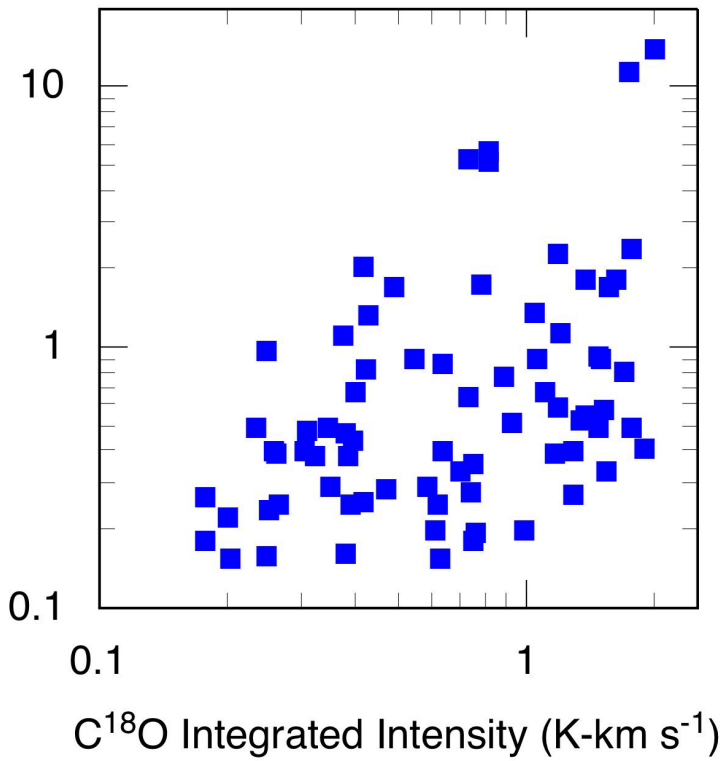
Water Cycle: Constraints from SWAS

Does the water vapor intensity correlate better with (believed) surface tracers than with (believed) volume tracers?

surface: CN N=1-0 113.14 GHz



volume: $C^{18}O$ J=1-0



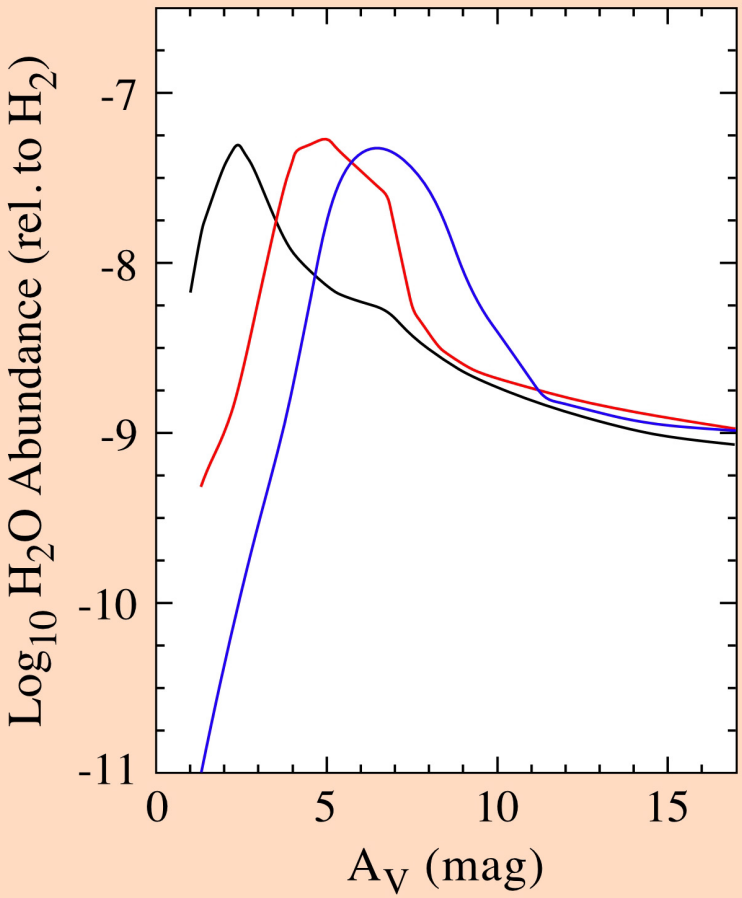
Water Abundance Structure in Quiescent Gas

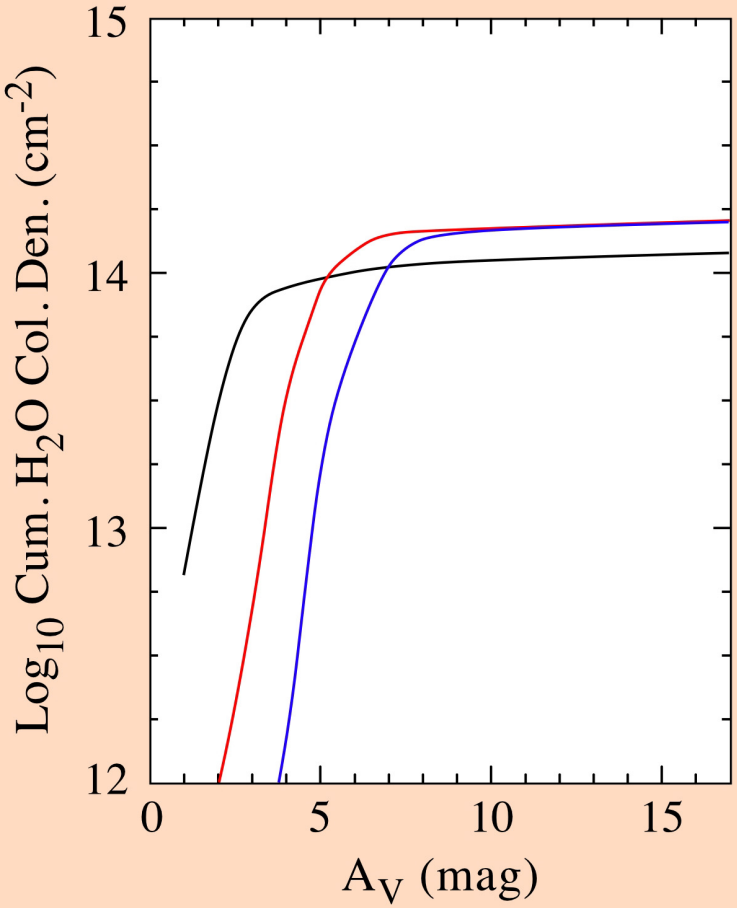
$n(H_2) = 2 \times 10^4 - 6 \times 10^5$ cm^{-3}

Time = 4×10^6 yrs

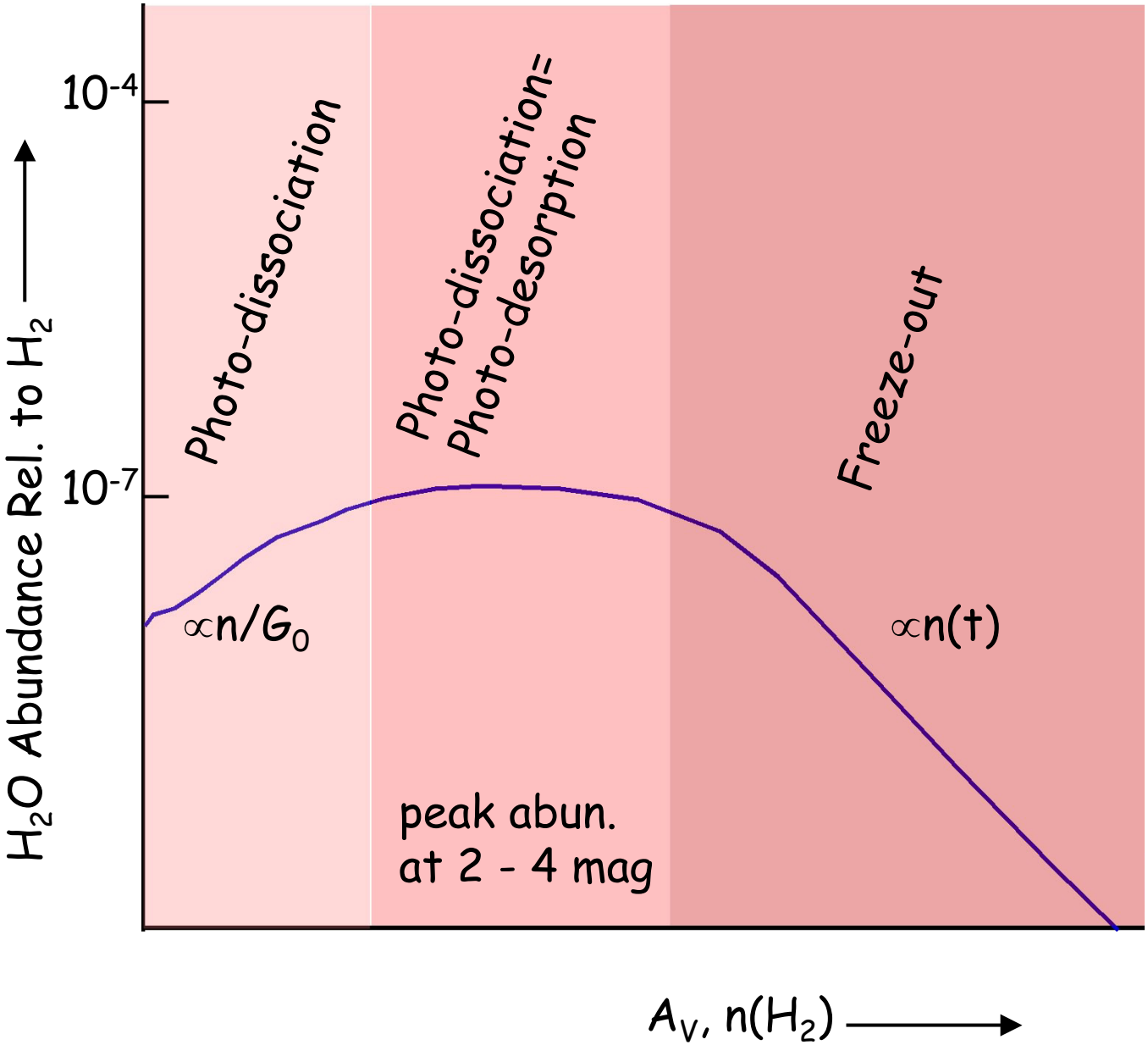
Photodes. Yield = 10^{-3}

$G_o = 1$ $G_o = 10^3$ $G_o = 10^5$





Water Abundance Structure in Molecular Clouds



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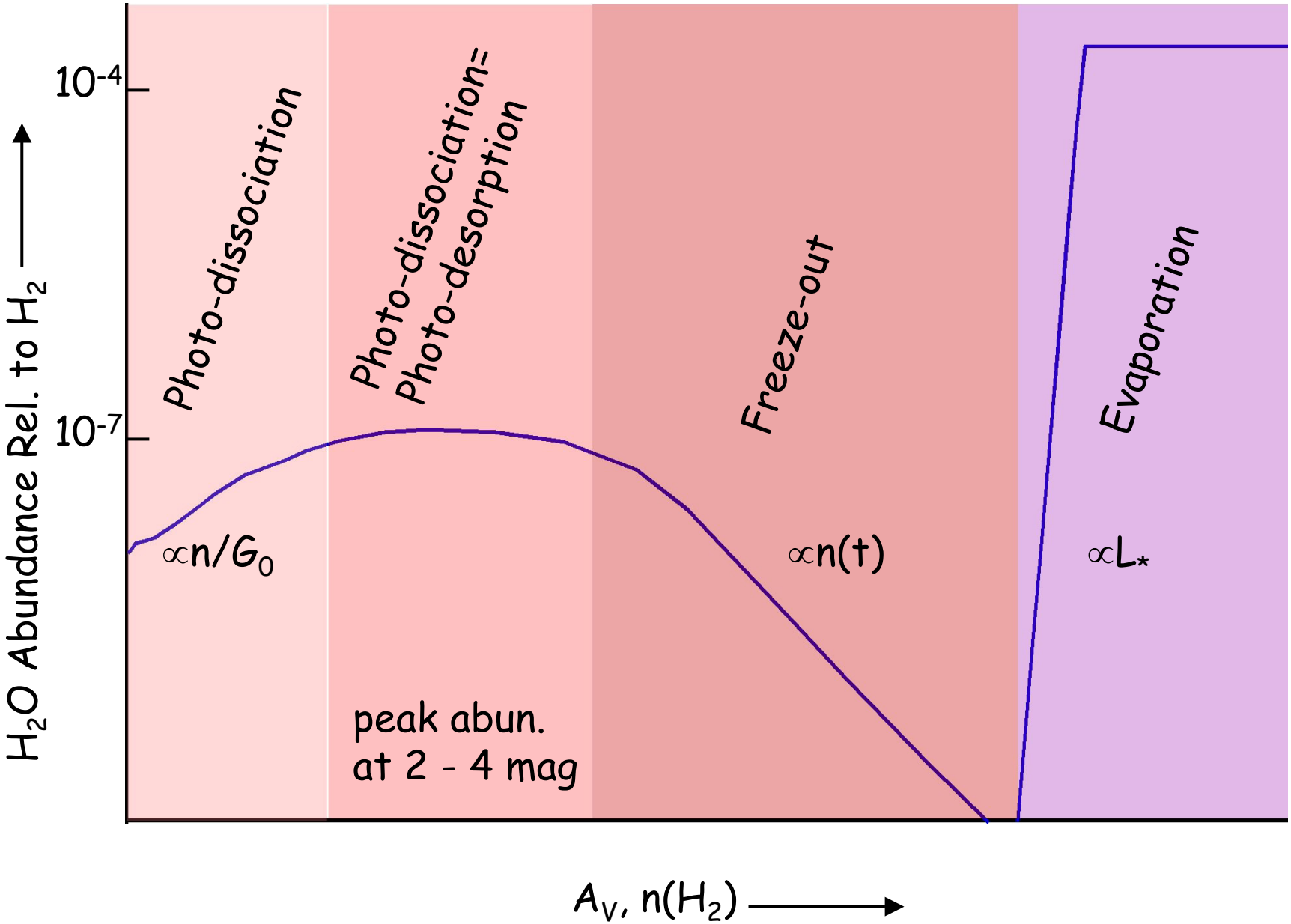
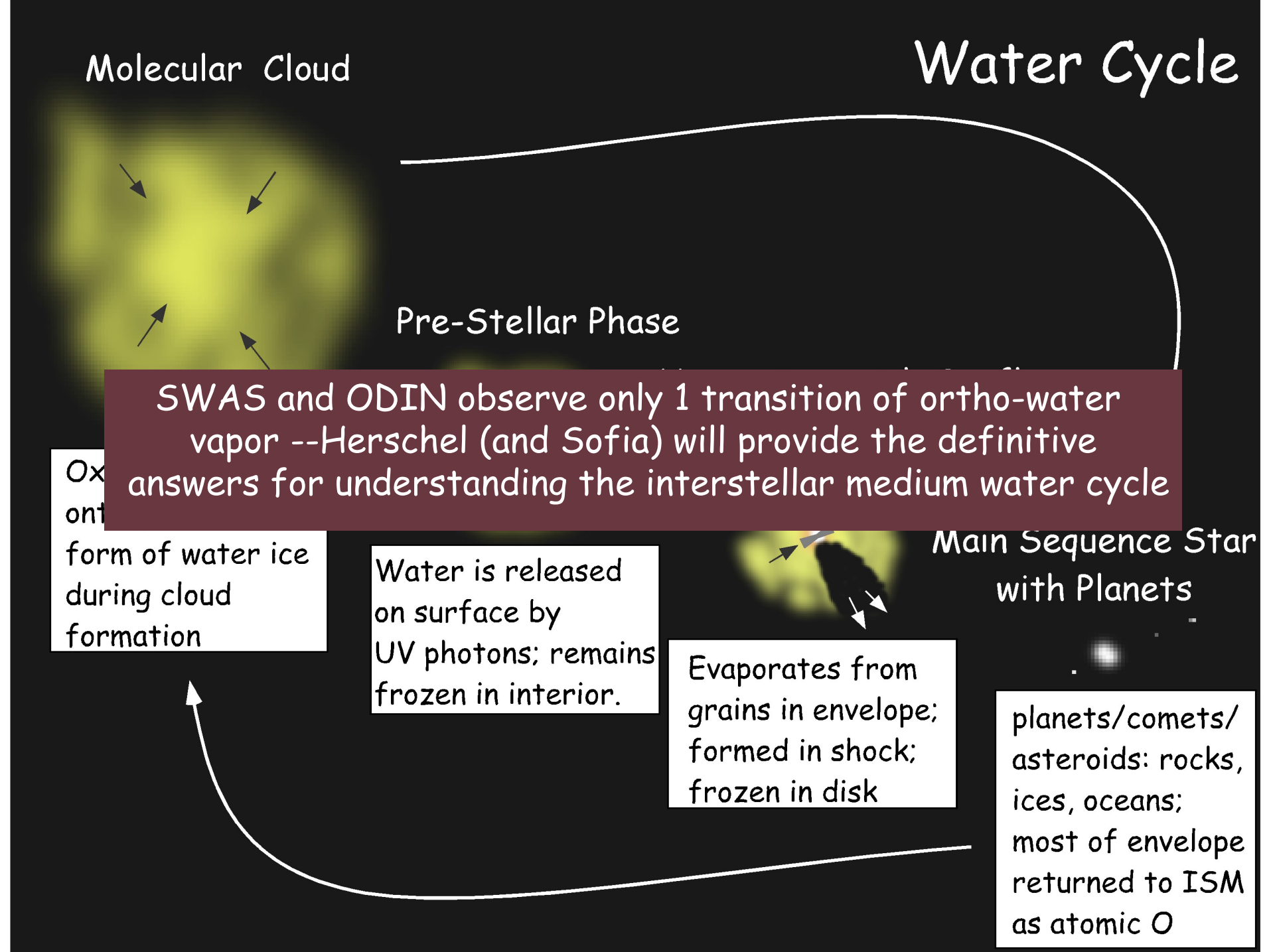
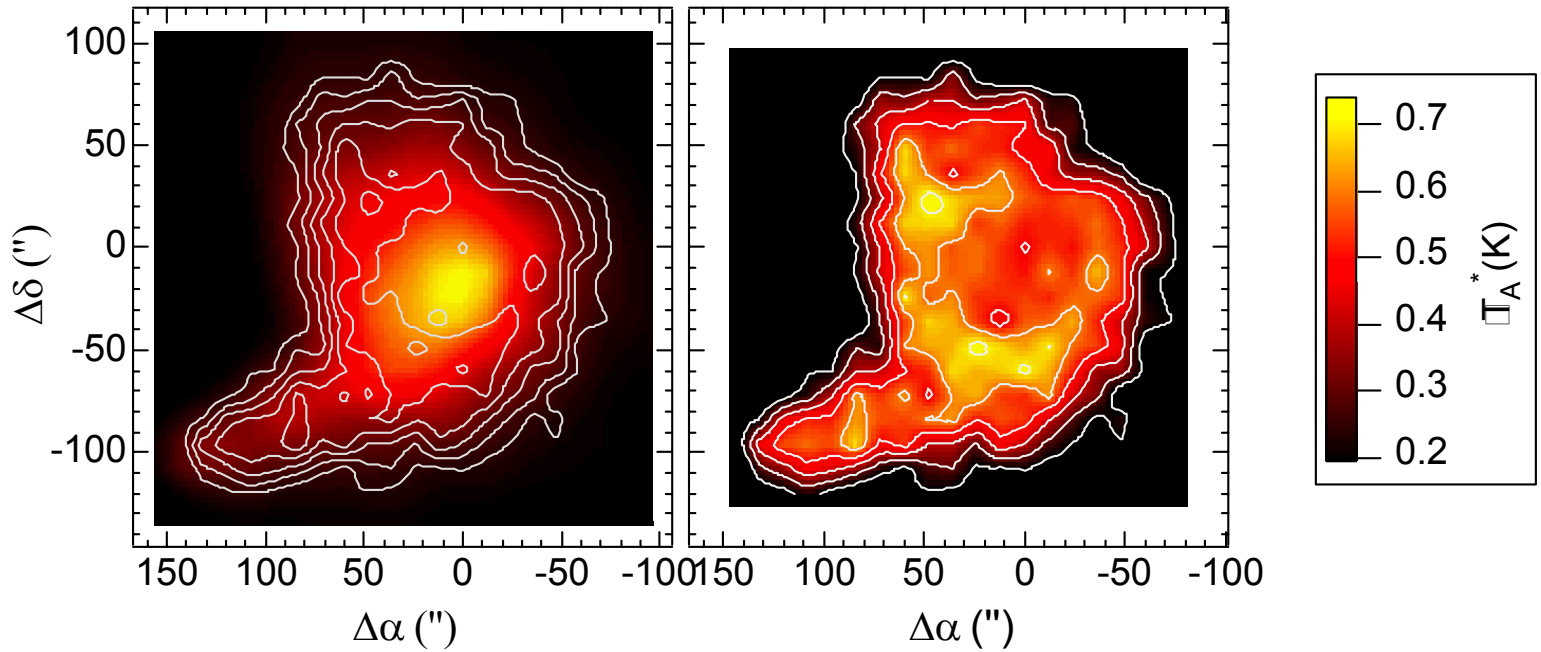



Molecular Cloud
Water Cycle
Pre-Stellar Phase
SWAS and ODIN observe only 1 transition of ortho-water vapor --Herschel (and Sofia) will provide the definitive answers for understanding the interstellar medium water cycle
Ox
ont
form of water ice during cloud formation
Water is released on surface by UV photons; remains frozen in interior.
Main Sequence Star with Planets
Evaporates from grains in envelope; formed in shock; frozen in disk
planets/comets/ asteroids: rocks, ices, oceans; most of envelope returned to ISM as atomic O

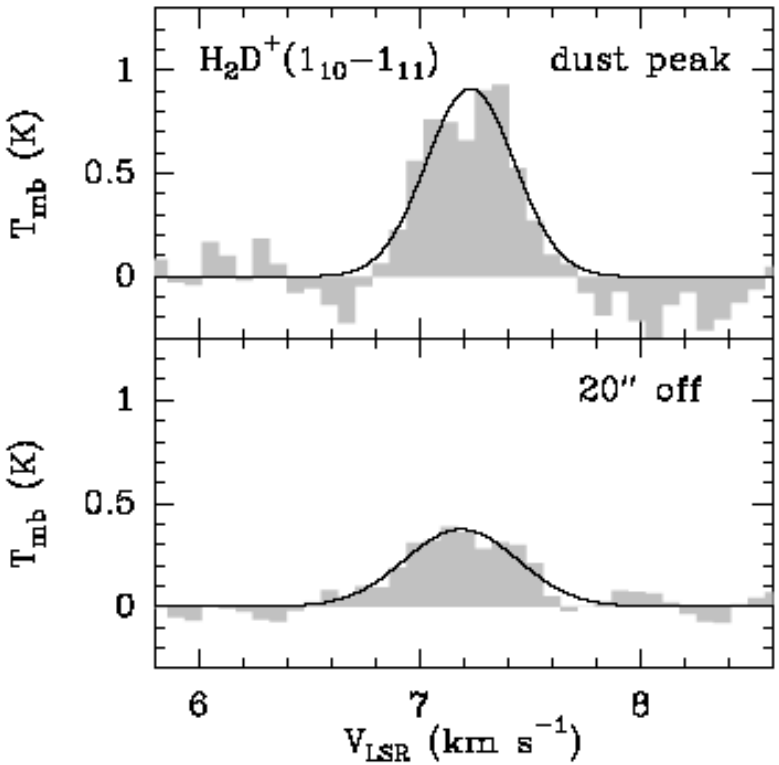
Beyond: Initial Conditions and Star Formation



- ground-based observations are suggesting that most, perhaps all, of the heavy elements are frozen on grain surfaces before a star forms.
- molecular line observations -- the only way to trace star formation dynamics -- are not tracing the dense center.
- 2 tracers left: H_2D^+ and D_2H^+

Beyond: Initial Conditions and Star Formation

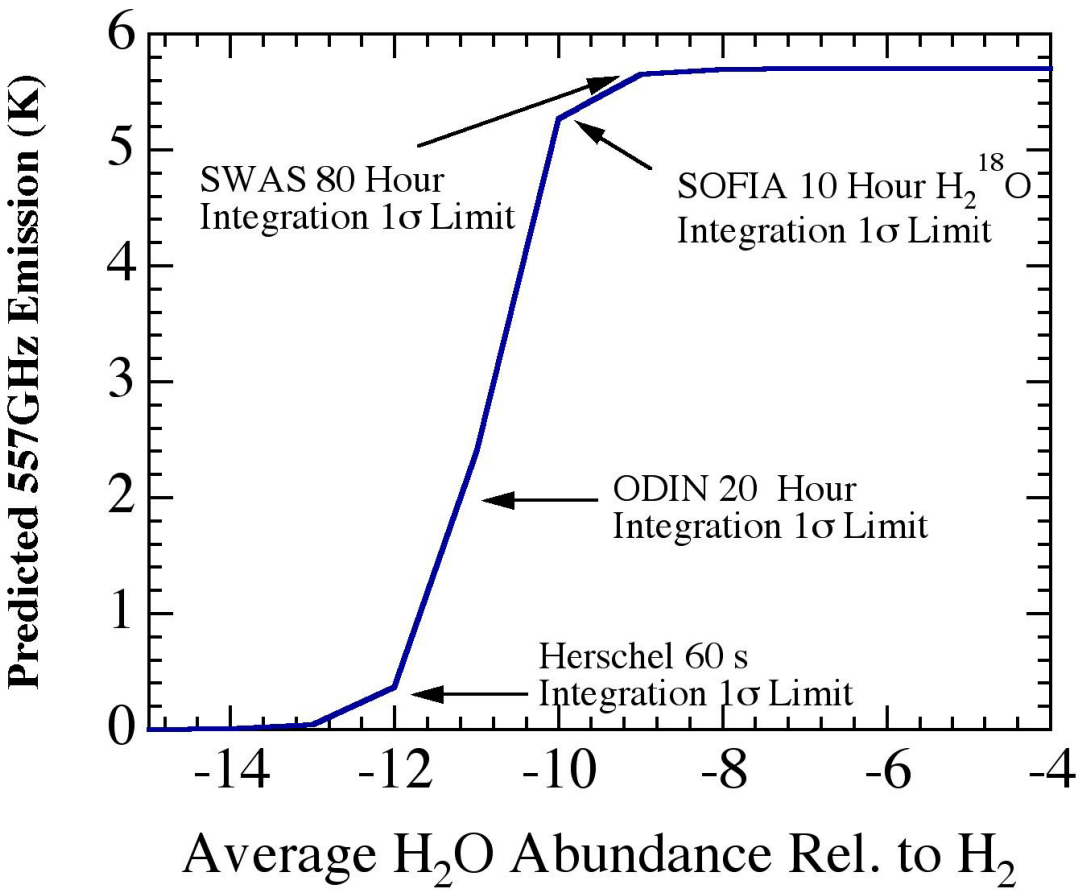
Detection of o-H_2D^+ (372 GHz) in star-less core by Caselli et al. (2003)



o-H_2D^+	372 GHz	ground-ALMA
p-D_2H^+	692 GHz	ground-ALMA
p-H_2D^+	1.37 THz	SOFIA
o-D_2H^+	1.48 THz	Her/SOF

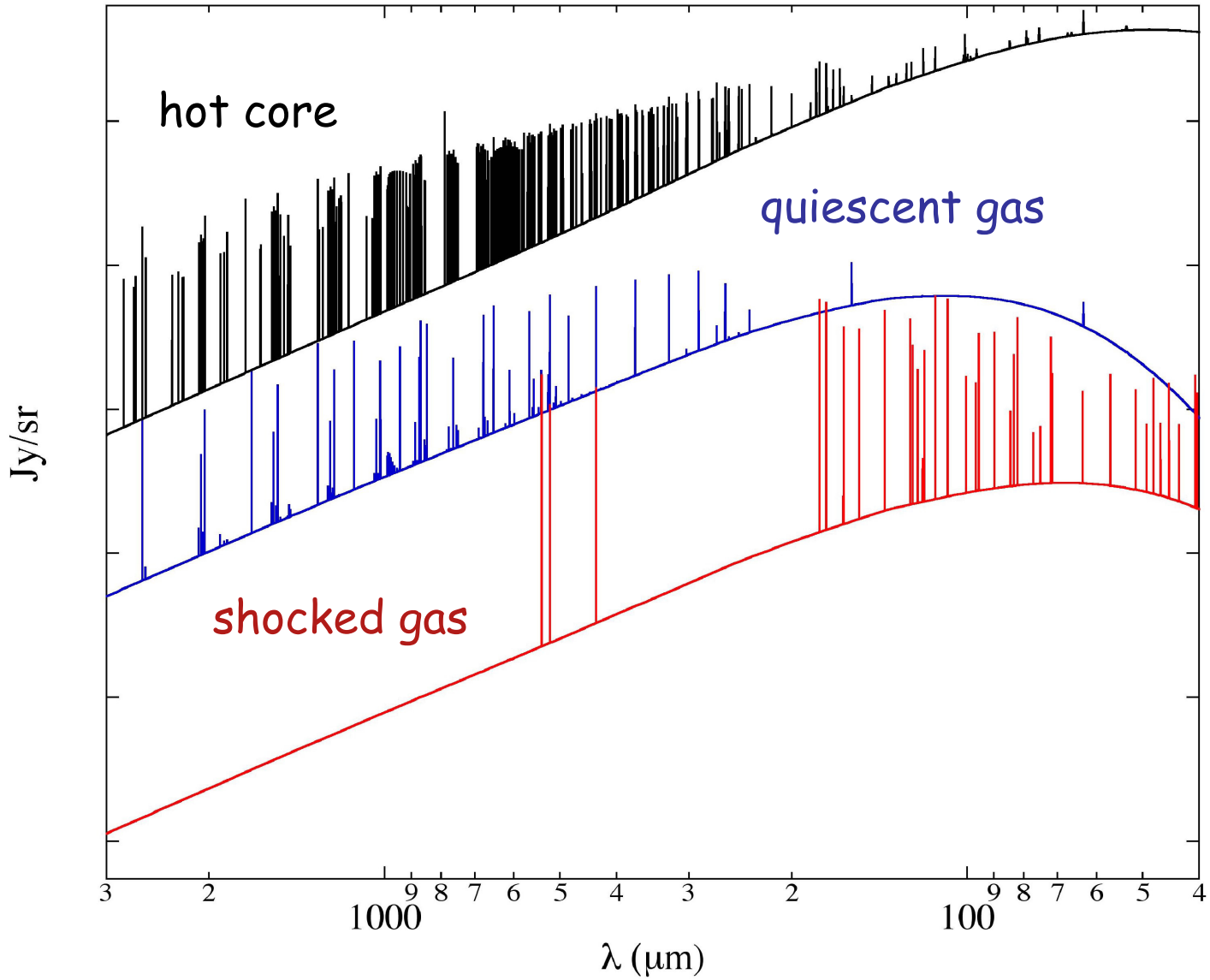
- ALMA can do it -- so why bother?
  - only 4 tracers - if all optically thin then no new information is obtained on dynamics.
  - based on L1544 and o/p < 1 -- then p-H_2D^+ will be thick!
- big, sensitive, space-borne telescope (SAFIR) or interferometer can
  - trace the kinematics!
  - bring resolution to bear in more distant high-mass SF regions -- where most stars are born.

Beyond: Water in Disks!



- Herschel should be capable of detecting water in TW Hya and a few other nearby systems.
- SAFIR will extend this capability to sources in Ophiuchus
- Interferometers might resolve the snow line!

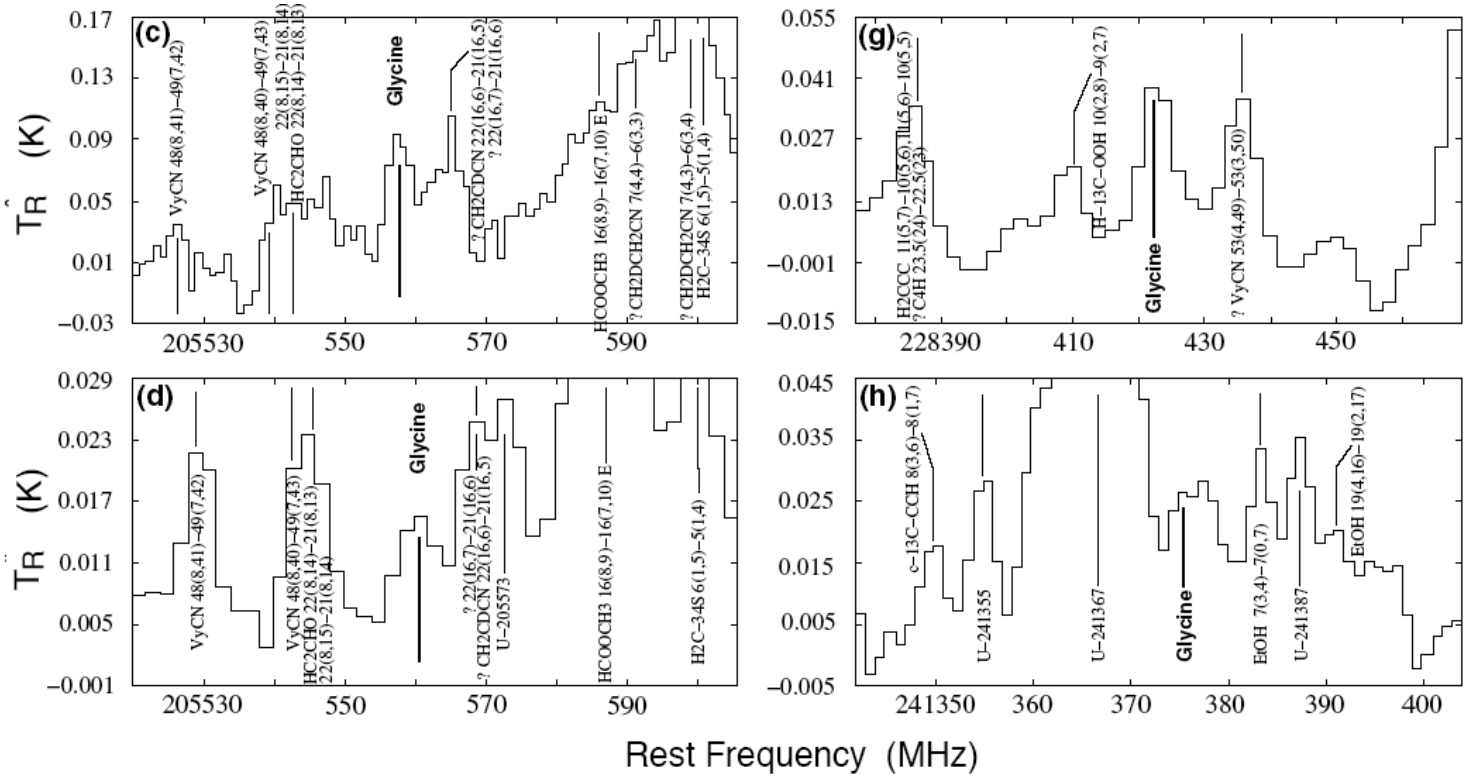
Conclusions: -- dreams of spectral coverage, low noise detectors, and high angular resolution.....



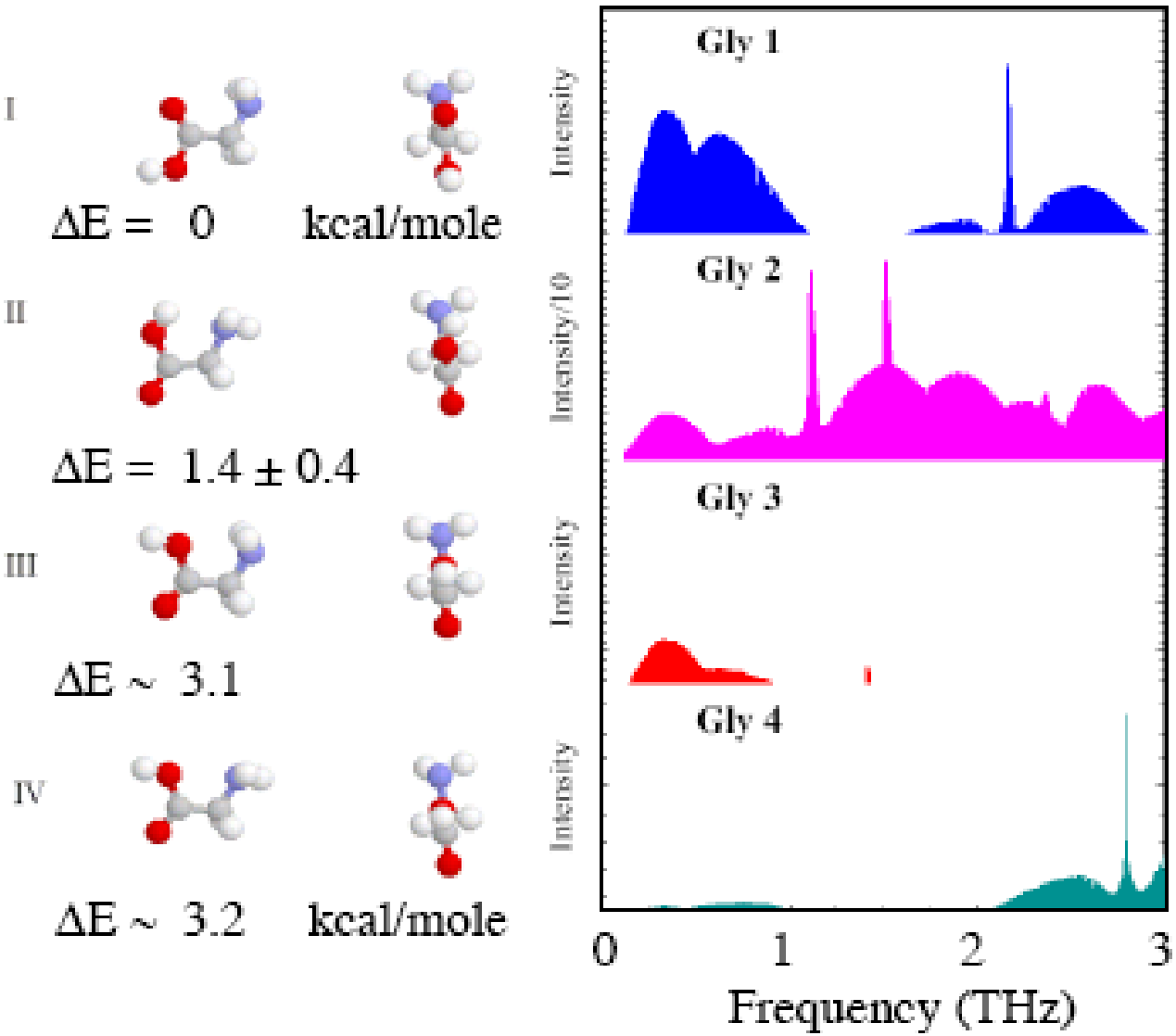
Astrobiology?

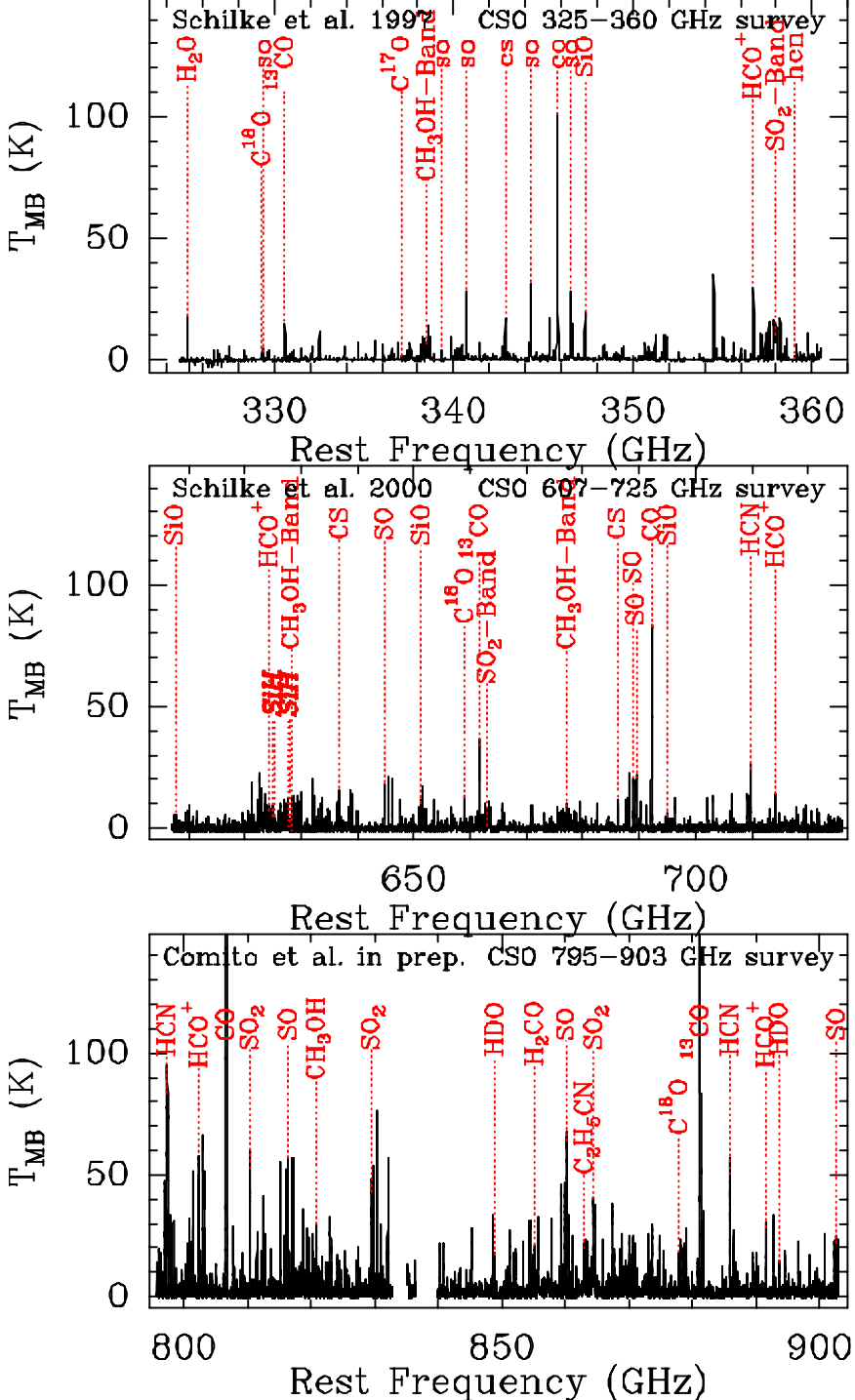
- Kuan et al (2003) claim a detection of interstellar glycine.
  - Disagrees with previous observations - of same sources - which suggest data is at line confusion limit (Combes et al. 1996).
  - CSO sub-mm surveys of Orion have reached line confusion limit at T_A ~ 1 K.

--> cannot use rotational transitions to detect molecules such as glycine



THz Spectrum of Glycine





- ground based line surveys:
  - detected thousands of lines
  - reached line confusion limit
  - demonstrated chemical complexity

Water Cycle: Constraints from SWAS

SWAS

H_2O 1_{10}-1_{01}

FCRAO

CN N=1-0

$C^{18}O$ 1-0